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Challenges & Opportunities in Propulsion Simulations

Venke Sankaran
AFRL/RQ

University of Michigan
Ann Arbor, 24 Sept 2015

AFRL Mission

Leading the discovery, development, and integration of affordable warfighting technologies for our air, space, and cyberspace force.

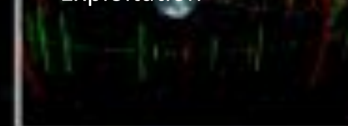
AFRL Technical Competencies

AF Office of Scientific Research
- Aerospace, Chemical & Material Sciences
- Education & Outreach
- Mathematics, Information, & life sciences
- Physics & Electronics

Aerospace Systems
- Air Vehicles
- Control, Power & Thermal Management
- High Speed Systems
- Space & Missile Propulsion
- Turbine Engines

Directed Energy
- Directed Energy & EO for Space Superiority
- High Power Electromagnetics
- Laser Systems
- Weapons Modeling and Simulation

Information
- Autonomy, C2, & Decision Support
- Connectivity & Dissemination
- Cyber Science & Technology
- Processing & Exploitation



Human Performance
- Bio-effects
- Decision Making
- Human Centered ISR
- Training

Munitions
- Fuze Technology
- Munitions AGN&C
- Munitions System Effects Science
- Ordinance Sciences
- Terminal Seeker Sciences

Sensors
- Advanced Devices & Components
- Layered Sensing Exploitation
- Multi-Int Sensing (RF/EO)
- Spectrum Warfare

Space Vehicles
- Space Electronics
- Space Environmental Impacts & Mitigation
- Space OE/IR
- Space Experiments
- Platforms & Operations Technologies

Materials and Manufacturing
- Functional Materials & Applications
- Manufacturing & Industrial Technology
- Structural Materials & Applications
- Support for Operations

Aerospace Systems Directorate

MISSION/VISION: Leading discovery and development of world class integrated Aerospace Systems S&T for national security

Aerospace Systems Directorate

~580 programs
(OH ~470 / CA ~110)

~1814 on-site people
(OH ~633 gov't, ~771 contractors)
(CA ~203 gov't, ~207 contractors)

~$540M / year (core S&T)
(FY14 PB includes FY14-FY18)
(OH ~$460M / CA ~$80M)

~$3.9B in facilities
(OH ~$1.9B / CA ~$2B)

Edwards AFB, CA

Established 1947

Technologies

- Liquid Rocket Engines
- Solid Rocket Motors
- Spacecraft Propulsion

Wright-Patterson AFB, OH

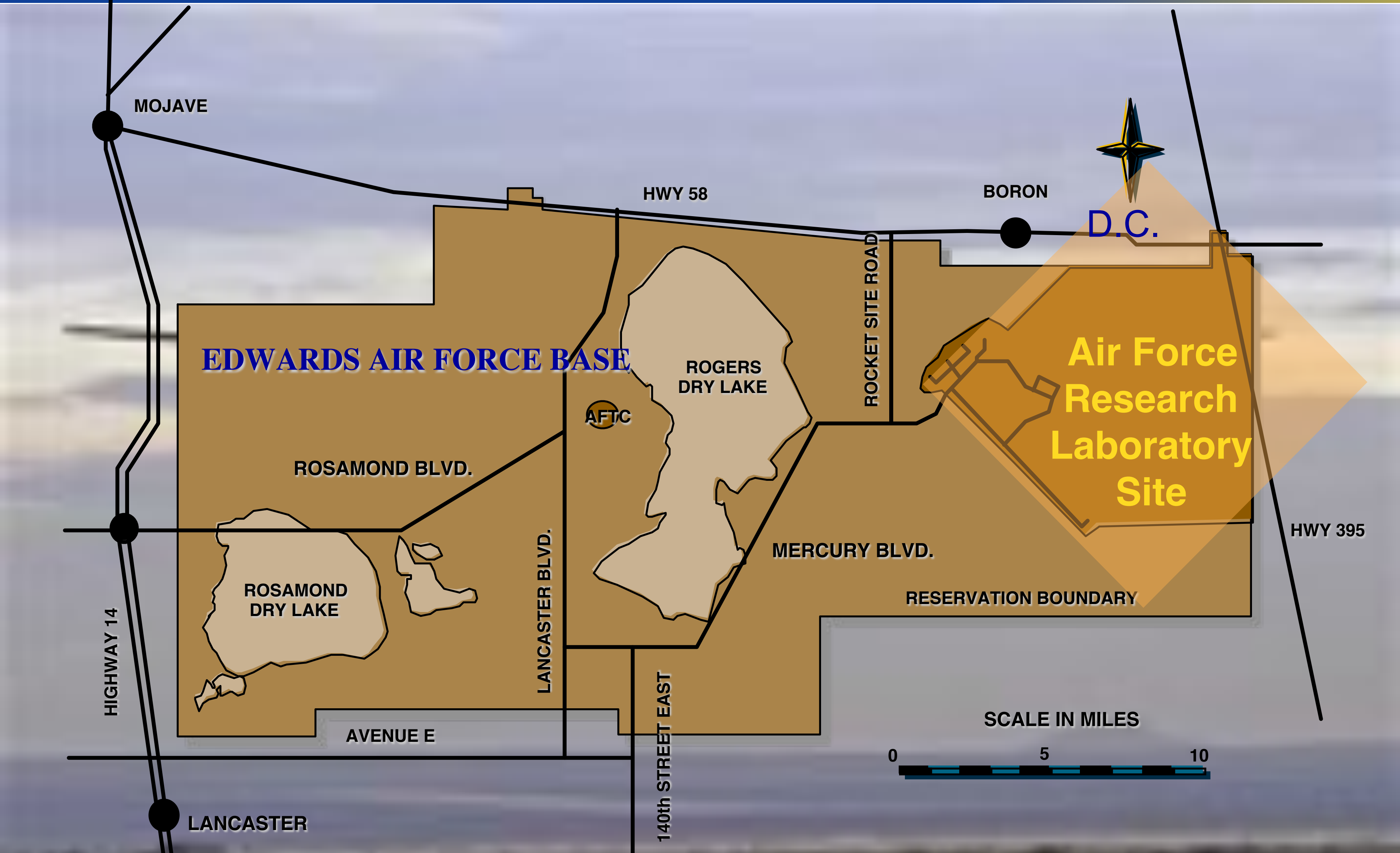
Established 1917

Technologies

- Gas Turbine Engines
- Vehicle Flight Systems
- Airframe Aerodynamics and Structures
- Hypersonic Propulsion

As of 31 July 2013

Edwards AFB



MOJAVE
HWY 58
BORON
D.C.
ROCKET SITE ROAD
EDWARDS AIR FORCE BASE
ROGERS DRY LAKE
AFTC
Air Force Research Laboratory Site
ROSAMOND BLVD.
ROSAMOND DRY LAKE
LANCASTER BLVD.
MERCURY BLVD.
RESERVATION BOUNDARY
HWY 395
HIGHWAY 14
AVENUE E
140th STREET EAST
SCALE IN MILES
0
5
10
LANCASTER

History of the Rock

- F-1 engine testing for the Saturn V Rocket that put Men on the Moon

Available Facilities

Bench-level Labs

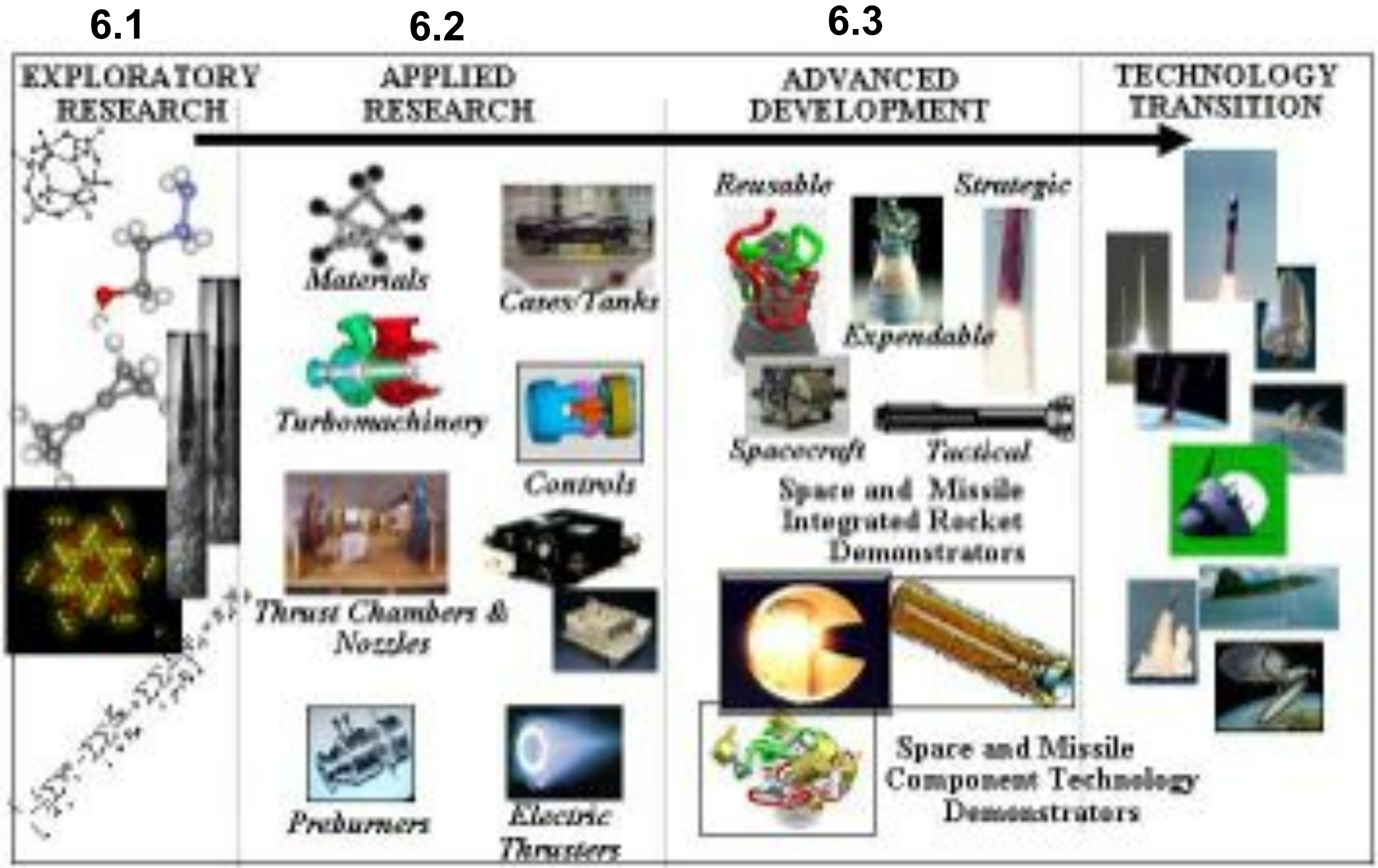
High Thrust Facilities

- 19 Liquid Engine stands, up to 8,000,000 lbs thrust
- 13 Solid Rocket Motor pads, up to 10,000,000 lbs thrust

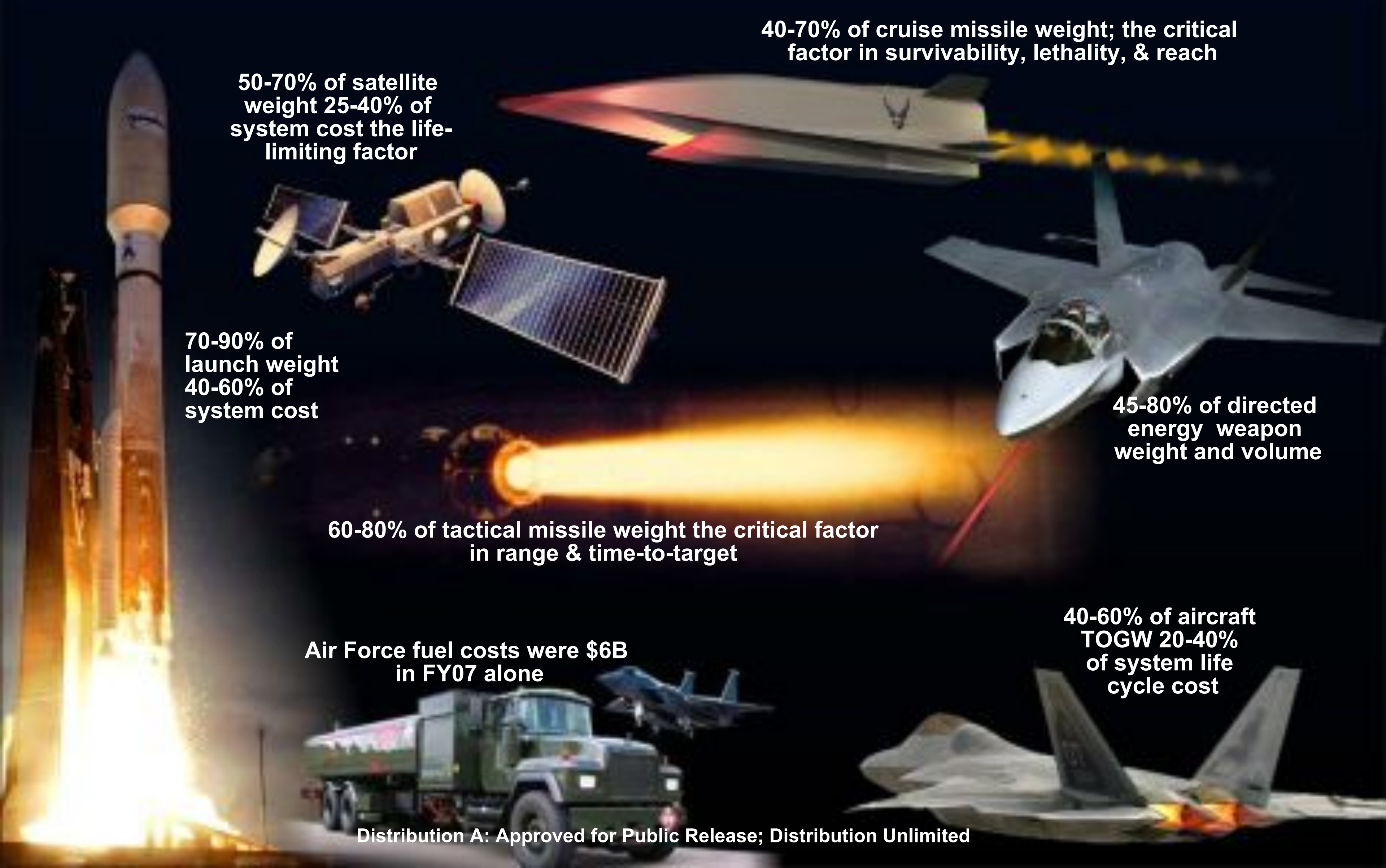
Altitude Facilities

- From micro-newtons to 50,000 lbs thrust

Space and Missile R&D Building Block Process



Propulsion & Power are Important!



Vision

Establish leadership in rocket M&S

- ❑ Maintain hands-on rocket M&S tool expertise
- ❑ Develop rocket physics and numerics expertise
- ❑ Promote modular computational infrastructures
- ❑ Lead in new and emerging research areas

Themes

Lead adoption of model-driven development

- Relevance to customers and programs
- Strong experimental interactions
- Model evaluation & development focus
- Partnership with community

Levels of Analysis

- ❑ Level 0 – Empirical relations
- ❑ Level 1 – 0D or 1D analysis
- ❑ Level 2 – Multi-dimensional analysis
- ❑ Level 3 – RANS coupled to multi-physics
- ❑ Level 4 – LES/DES/DNS simulations

Combustion CFD example

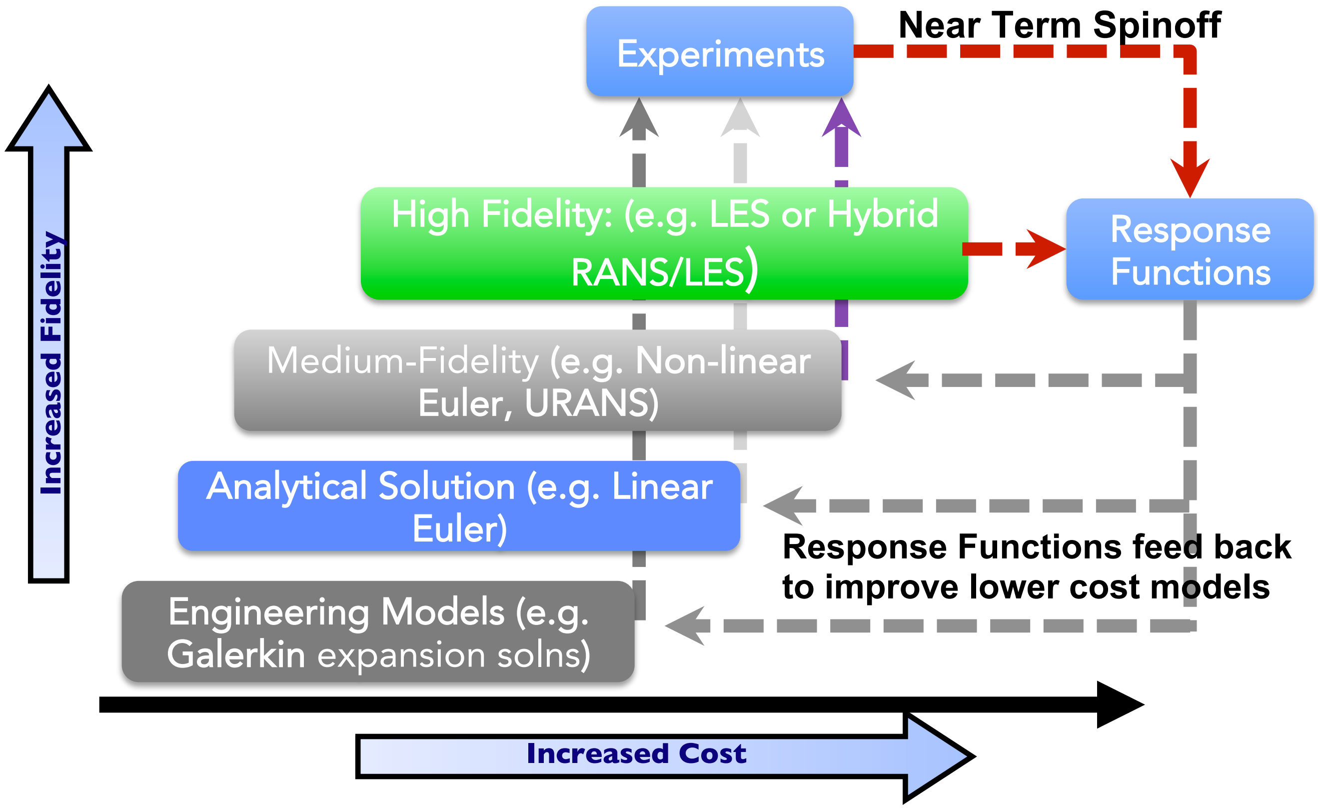
Types of Codes

- ❑ Commercial – Fluent, STAR-CCM
- ❑ Small Business – CRAFT, CFD++
- ❑ University/In-house – LESLIE, GEMS
- ❑ Open-Source – OpenFOAM
- ❑ Govt Codes – NCC, Coliseum, CREATE

A combination of code solutions is necessary!

Multi-Level Hierarchy

Utilize high-fidelity solutions to develop next-gen design tools



Combustion stability example

Data-Centric Model Development

Anderson (Purdue)
- AFOSR
- NASA CUIP
- ALREST
- AFRL

Frederick (UAH)
- NASA CUIP
- AFRL
- ALREST

Karagozian (UCLA)
- AFOSR

Leyva, Talley (AFRL)
- AFOSR
- ALREST

Cavitt (Orbitec)
- AFRL
- ALREST

Santoro (PA State)
- AFOSR (core)
- NASA CUIP
- ALREST

Yu (Maryland)
- NASA CUIP

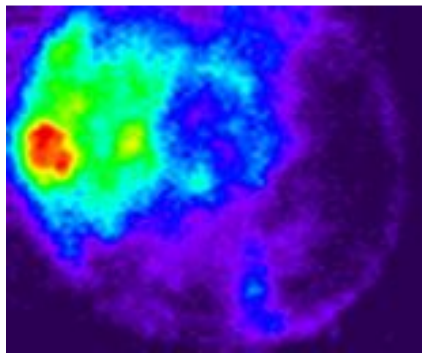
Zinn (GA Tech)
- AFOSR

Nestleroad Engin'ng
- MDA

Experiments

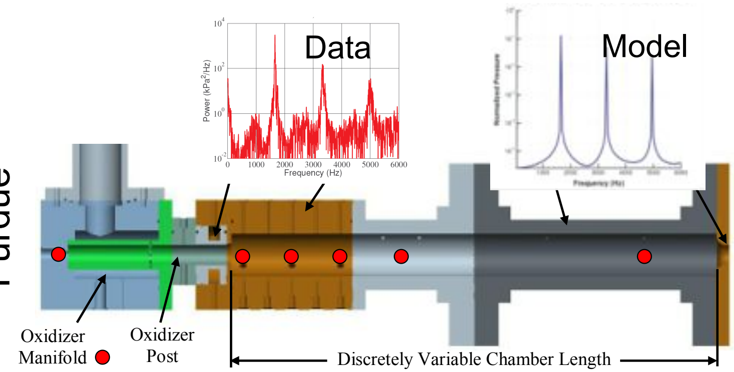
Spinning CI

GA Tech



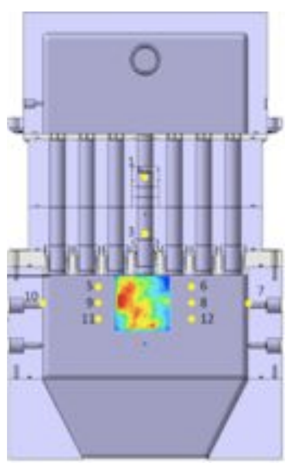
Longitudinal CI

Purdue

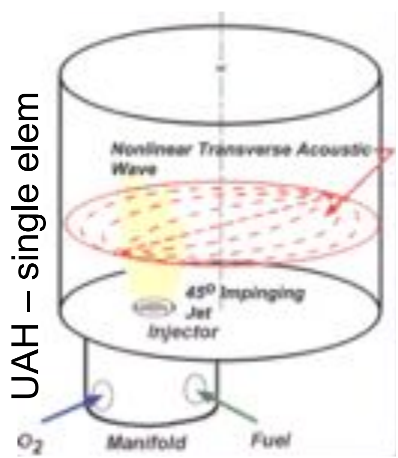


Standing CI

Purdue – multi elem

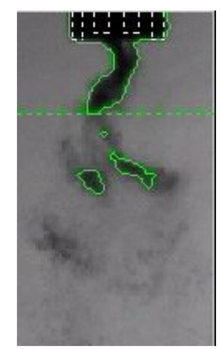


UAH – single elem



Driven jets

AFRL - coax



Acoustics

Full Scale (existing and HCB)

HCB to be heavily instrumented to provide CI data

Payoffs

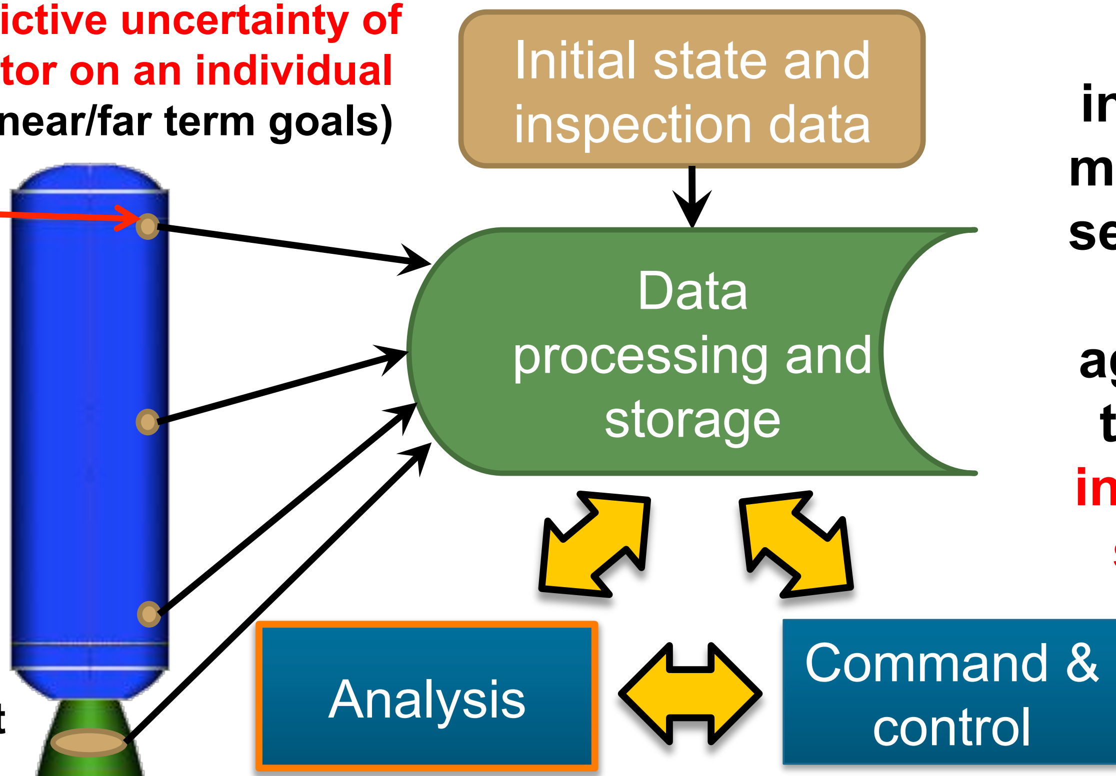
Damaged F-1 engine injector faceplate
due to combustion instability

- The Past: Test Driven Development
  - F-1 > 3000 tests (59 R&D engines)
  - J-2 > 1000 tests (43 R&D engines)
  - SSME >900 tests (27 R&D engines)
  - RL-10 >700 tests
- The Future: Model Driven Development
  - 20-50 tests??
  - ICBMs: $25B in Life Cycle Cost savings

Integrated Motor Life Management

Goals: **Reduce predictive uncertainty of future state of a motor on an individual basis by 20%/50%** **(near/far term goals)**

Sensors **to include: temperature, humidity, case damage, propellant slump, acceleration, and TVA displacement and load**



First integration of motor specific sensor data to advanced aging models to provide a individualized service life estimate

In-House:

- Validation of A&S modeling capability
- AFNWC funded supported for ANDES improvement (Automated NDE Data Evaluation System)

The WOWs

- Potential to provide >20% reduction in LCC
- Provide accurate, near-real-time motor health condition (diagnostics)
- Provide individualized service life estimates (prognostics)
- Transition opportunity ~ 2018

MCAT
(Motor Component Assessment Technology)

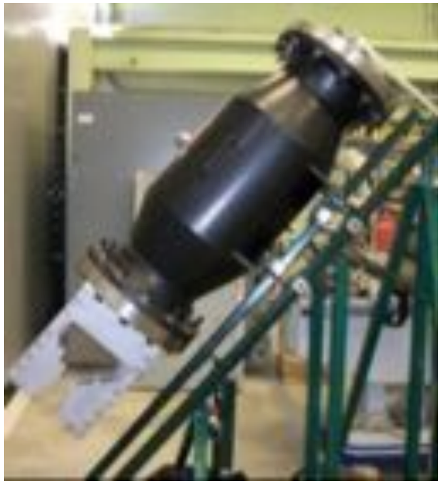
What are we doing? Developing new solid rocket motor (SRM) components and M&S tools that decrease inert weight by 20%.

Customer why? High-speed penetrator weapons will enable attack of deeply-buried targets.

Tech Reason? New M&S tools may show possibility of higher efficiencies from SRM designs.

Transition? 3 of 6 FY12 task orders support an AFRL FCC. 1 of 6 FY12 task orders supports AFNWC

In-House:
Experiments to validate new models



The WOWs

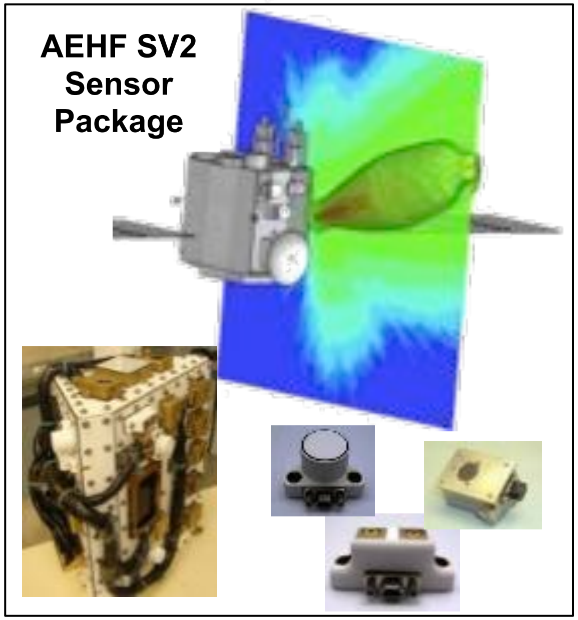
- **The AFNWC propellant task is part of a plan that may save $2.1B in future acquisition costs**
- **We are only gov't lab doing solid rocket motor R&D for launch & strategic needs**

Electric Propulsion

Plasma propulsion increases Isp by 10x, reducing s/c propellant 10x, lighter and/or more capable s/c

Developing new technologies that enable less expensive, more maneuverable and agile s/c

Reducing launch mass substantially reduces launch cost, increases payload fraction, and enables missions otherwise not possible



In-House:

- Test facilities
  - 8 vacuum chambers
  - Thruster design
  - Diagnostics
  - Validation
- Advanced numerics

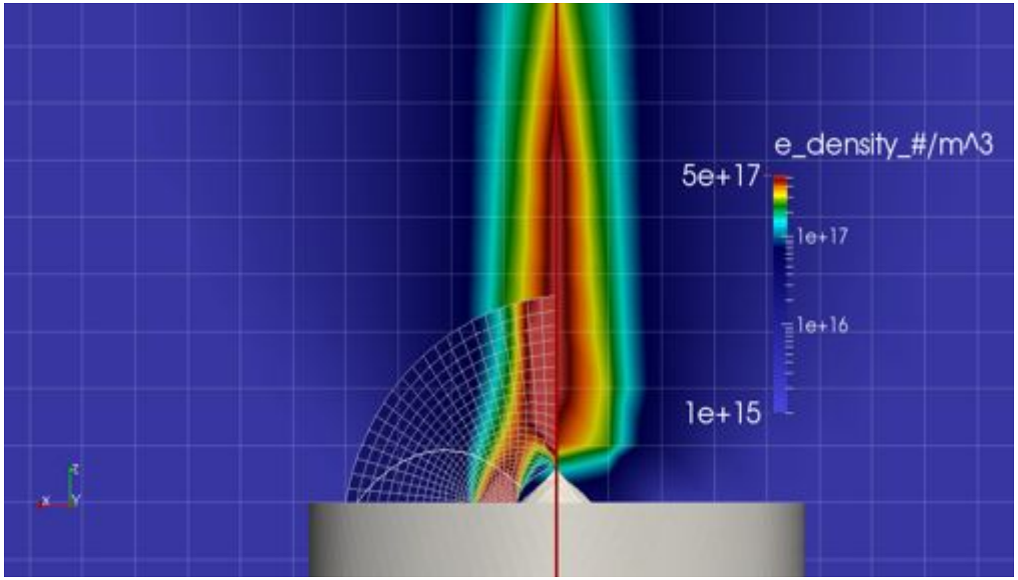
The WOWs:

- AEHF requested assistance with thruster performance verification
- Developed propulsion module for FalconSat-5 tech demo, including spacecraft interaction diagnostics
- Cubesat EP propulsion module selected by 2 constellations
- National M&S effort for EP coordination

Coliseum

OBJECTVES

- Engineering tool to study EP plumes and their effect on spacecraft
  - Realistic Geometries
  - Flexible Materials databases



APPROACH

- Develop C-based framework code (Coliseum) and plasma submodules (Draco, Aquila, Ray)
- Couple with HPHall – hybrid fluid/PIC code

Realtime coupling between HPHall and Coliseum allows us to track evolution of time dependent features all the way from the anode to many thruster lengths downstream

Next-Gen Framework

OBJECTIVES

- Need new computational framework to leverage modern computer science, algorithms and hardware acceleration and provide much-improved capabilities to user base

APPROACH

- Build modular C++ object-oriented framework with architecture to leverage Nvidia GPU accelerators
  - Release common computational infrastructure as Distro A for collaboration
  - Add physics modules as either Distro C or A to accomplish ITAR mission

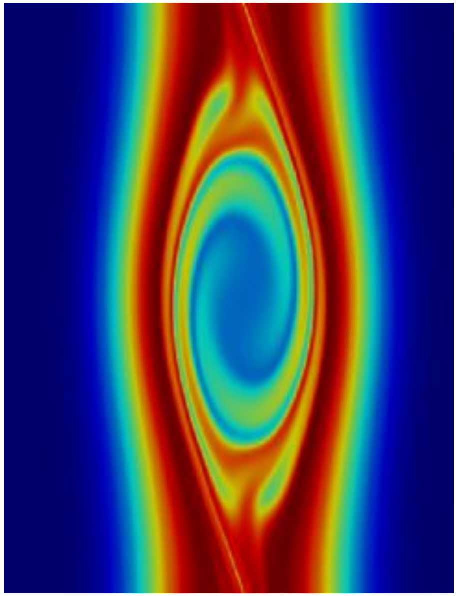
LOOKING AHEAD

- Version 1 (est. beta release end of 1QFY16)
  - Coliseum replacement capability
    - Electrostatic pushes
    - Triangulated spacecraft geometries
    - Electrostatic plasma solvers (Boltzmann & Poisson)
    - Volumetric collisions
    - Hooks to communicate with HPHall
    - Macroparticle surface/boundary interactions
- Version 2 (est. beta release end of 4QFY16)
  - HPHall replacement capability
- Version 3+
  - Higher fidelity device models (HET and FRC)

Basic Plasma Propulsion Research

APPROACH

- Develop hybridized fluid / kinetic solvers to efficiently study multiple scales present in many plasma processes
- Develop more computationally efficient, higher-fidelity Collisional-Radidative (C-R) and radiation transport models to improve simulations and mirror experiments
- Hybridize Vlasov and multifluid models
- Apply advanced fluid simulation methods to FRC to develop true design capability

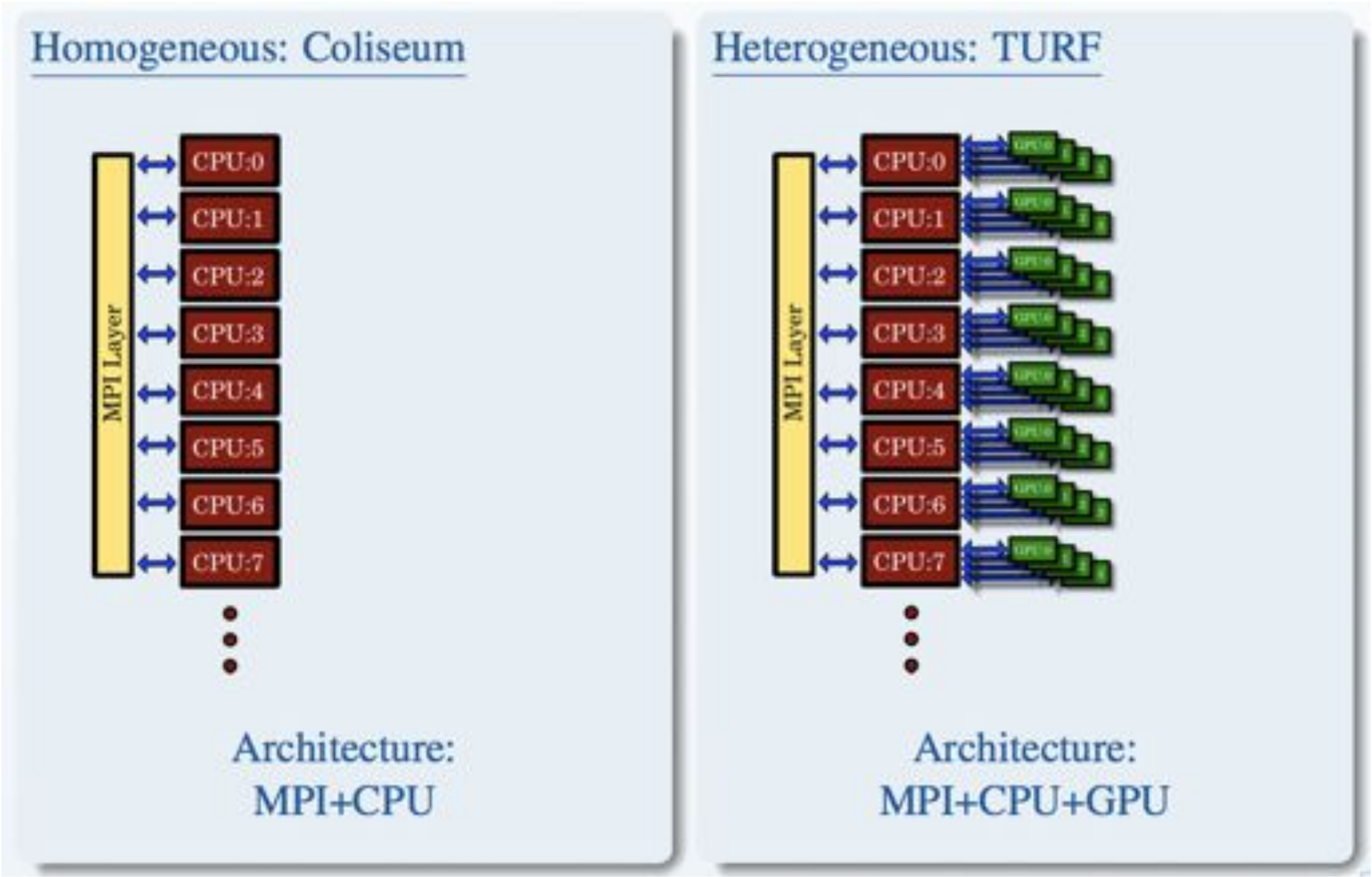


Two-stream plama instability (Vlasov)

IMPACTS

- Close coupling of 6.1/6.2 programs enables cutting edge academic and lab research to transition into engineering codes
- Provides exceptionally qualified workforce

Hybrid CPU-GPU Framework



Titan vs. Summit

Feature	Titan	Summit
Application Performance	***Baseline***	***5-10x Titan***
Number of Nodes	***18,688***	***~3,400***
Node performance	***1.4 TF***	***> 40 TF***
Memory per Node	***38GB (GDDR5+DDR3)***	***>512 GB (HBM + DDR4)***
NVRAM per Node	***0***	***800 GB***
Node Interconnect	***PCIe 2***	***NVLink (5-12x PCIe 3)***
System Interconnect (node injection bandwidth)	***Gemini (6.4 GB/s)***	***Dual Rail EDR-IB (23 GB/s)***
Interconnect Topology	***3D Torus***	***Non-blocking Fat Tree***
Processors	***AMD Opteron™ NVIDIA Kepler™***	***IBM POWER9 NVIDIA Volta™***
File System	***32 PB, 1 TB/s, Lustre®***	***120 PB, 1 TB/s, GPFS™***
Peak power consumption	***9 MW***	***10 MW***

Source: R. Sankaran, ORNL

Hydrocarbon Boost

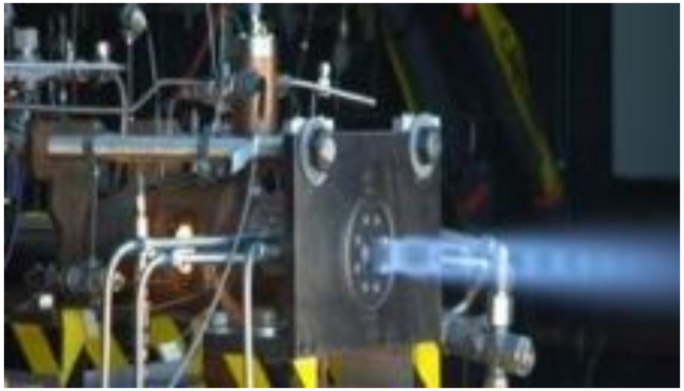
Advanced LRE Tech Base

– Required to replace Russian RD-180 on EELV

– Establishes Ox-rich staged combustion (ORSC) tech base for U.S.

In-House:

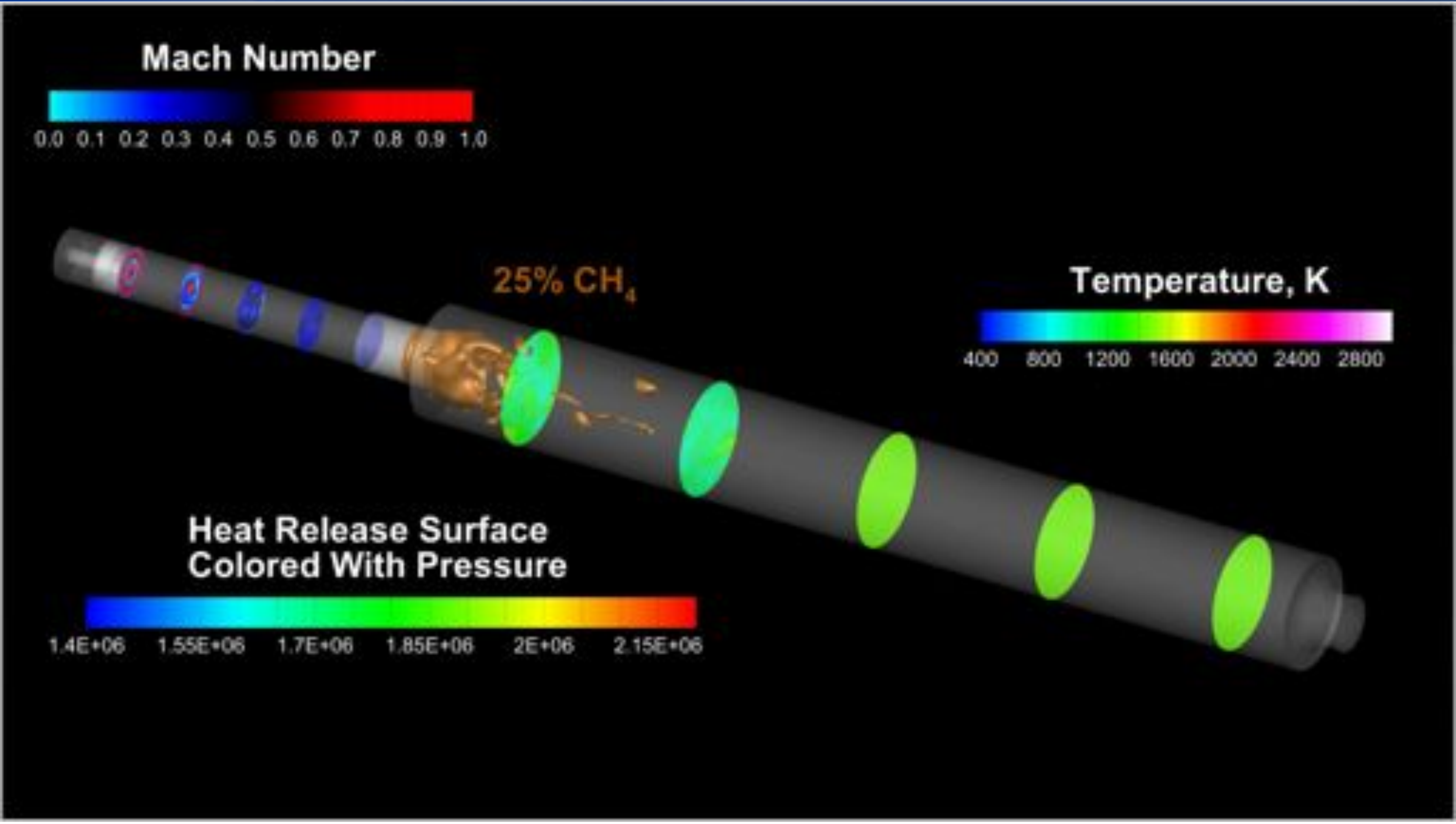
- Subscale facility to mitigate combustion stability risk



The WOWs:

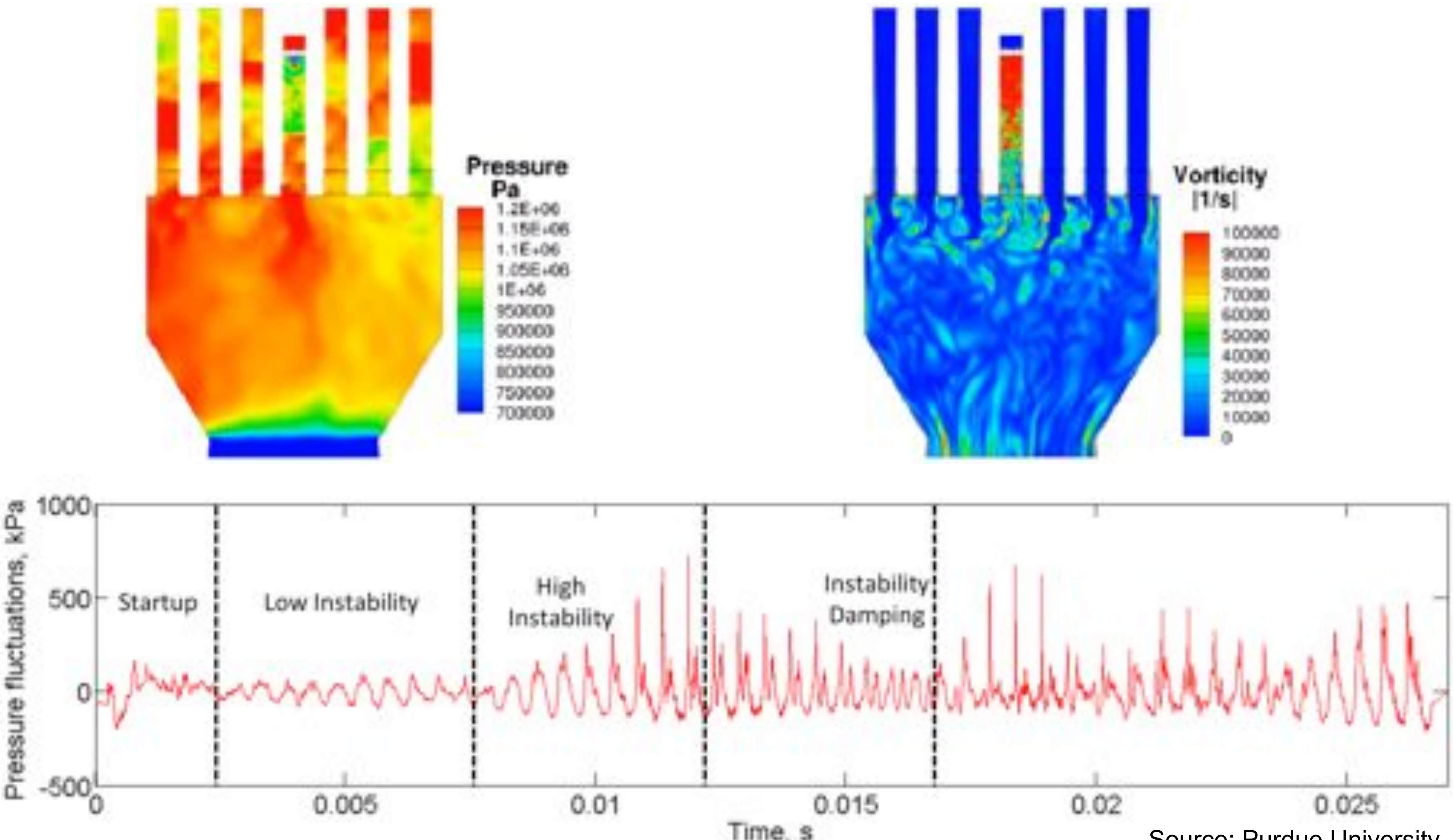
- Design, build, test ORSC LOx/ Kerosene Liquid Rocket Engine Tech Demonstrator
  - 250K-lbf with high Throttle Capability
  - 100 Life Cycle with 50 cycle overhaul

Liquid Rocket Combustion Instability



Source: Purdue University

Transverse Mode Instabilities



Source: Purdue University

Next-Gen R&D

High-Fidelity

- Modular framework
- Efficient grid types
- High-Order Accuracy
- Adaptive Mesh
- Adaptive Physics
- Advanced models
- Emerging architectures

SPACE – SCALABLE PHYSICS-BASED ADVANCED COMPUTATIONAL ENGINEERING

Multi-Fidelity

- Use high-fidelity to train low fidelity
- LES simulations
  - Limited number off-line calculations with DOE
- Reduced Order Model
  - Obtain response functions from LES
- Design Tool
  - Non-linear Euler with response functions

Mesh Types for Reacting-LES

Unstructured Mesh

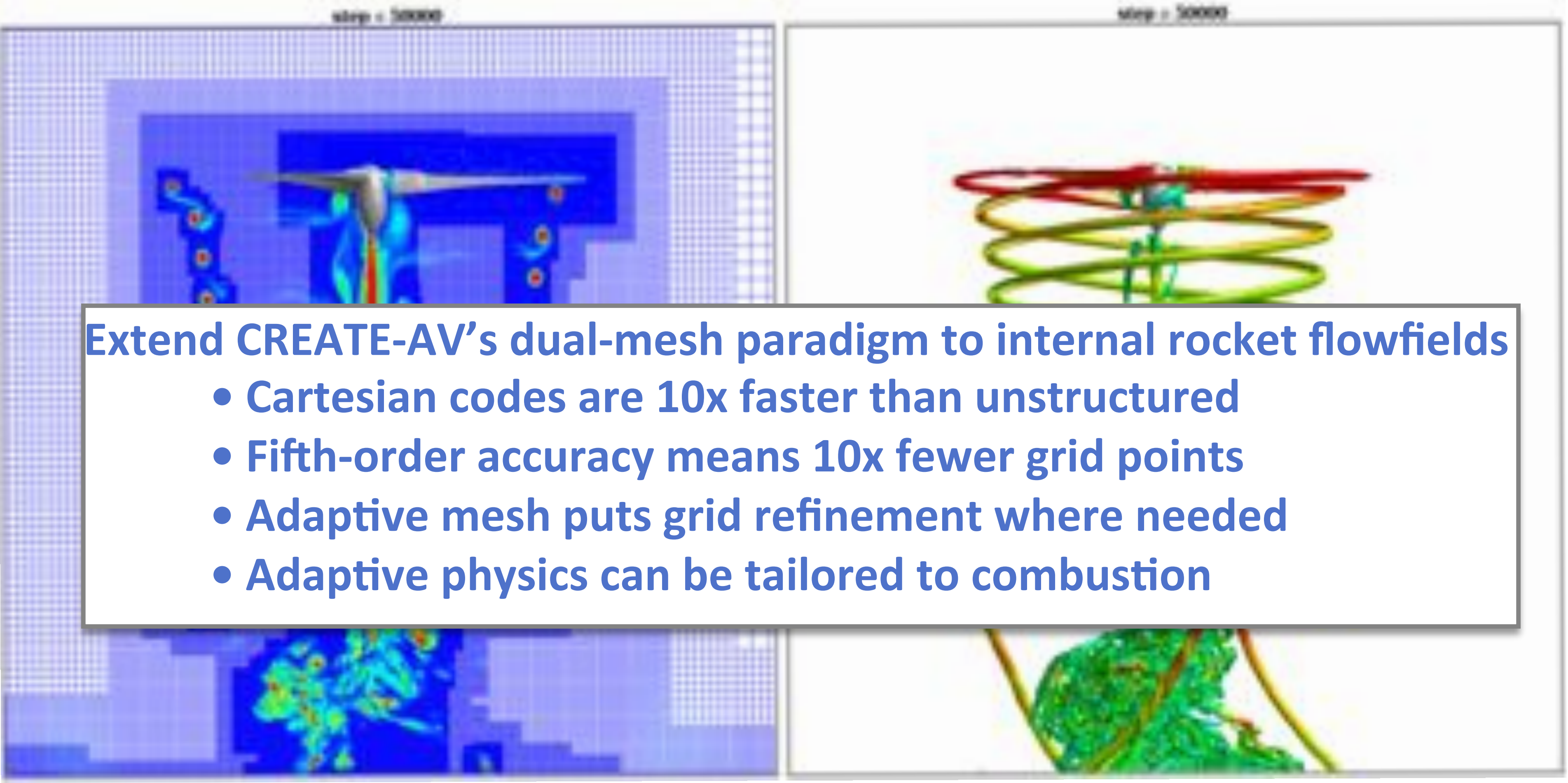
- **Rarely automated**
- **Very inefficient**
- **Usually limited to second-order accuracy**
- **Difficult to adapt**
- **Good at capturing complex geometries**
- **Very good for boundary-layer resolution**

Cartesian Mesh

- **Automatic generation**
- **Highly efficient**
- **High-order accuracy**
  - Usually fifth- or seventh-order accurate
- **Amenable to adaption**
- **Poor geometry definition**
- **Proper boundary-layer resolution is inefficient**

Solution:
Combine unstructured near-body mesh with Cartesian off-body mesh

Dual-Mesh Paradigm



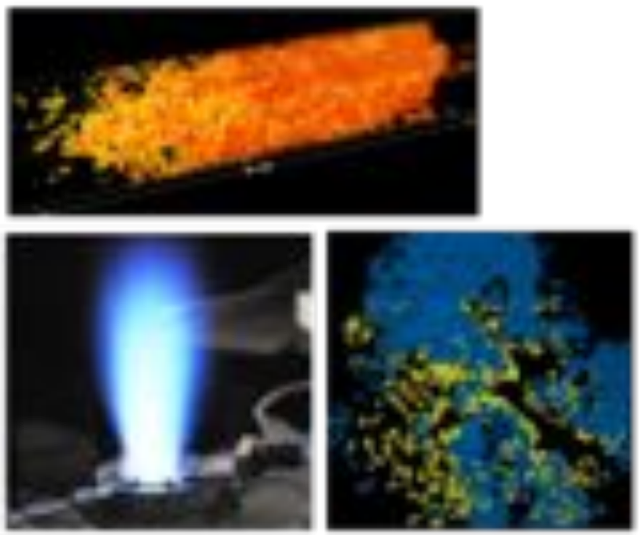
Extend CREATE-AV's dual-mesh paradigm to internal rocket flowfields

- **Cartesian codes are 10x faster than unstructured**
- **Fifth-order accuracy means 10x fewer grid points**
- **Adaptive mesh puts grid refinement where needed**
- **Adaptive physics can be tailored to combustion**

Source: Wissink et al., CREATE

Turbulent Combustion

Fundamental Flame Properties → Modeling Foundation → Real Engine Simulation



Basic Model Assumptions & Validation Procedures

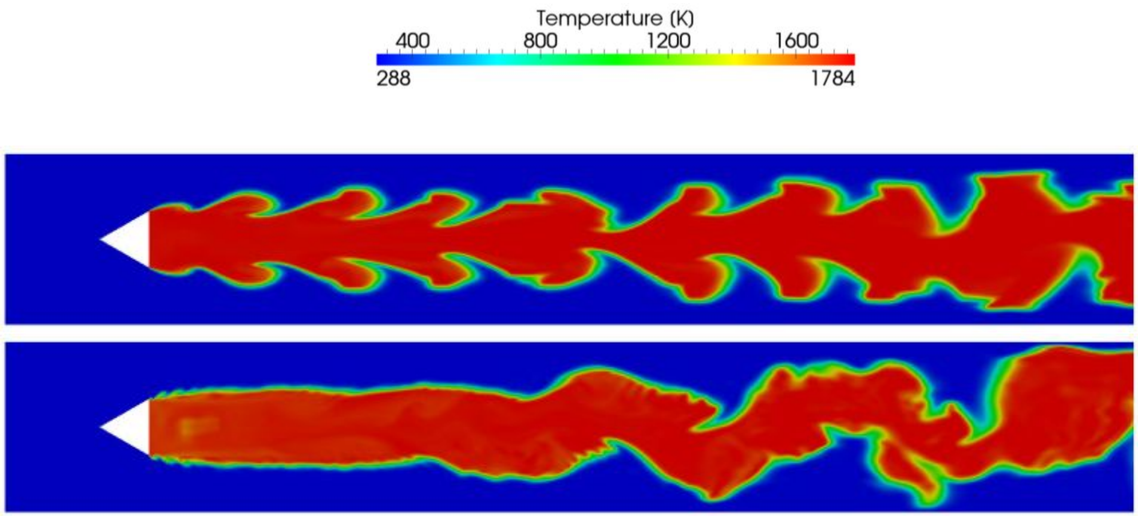
- Flamelets
- LEM
- PDF/FDF
- New, Improved Models

cyclic heat release

Advanced Numerics

Algorithm comparisons:
- Identical SGS
- Differences in numerical schemes' dissipation

Premixed flame:



MUSCL scheme

Central scheme

LESLIE3D

Ref: 2014 – Cocks et al. "Towards Predictive Reacting Flow LES"

Need to determine **OPTIMAL** discretization schemes for Reacting LES

Adaptive Physics

- **Combustion calculations are extremely expensive**
  - Detailed combustion kinetics
    - Entails large numbers of species and reaction steps
  - Turbulent combustion closures
    - Linear Eddy Model (LEM) involves sub-grid solutions
- **The “Silver Lining“**
  - Detailed chemistry and closures only needed locally
  - Most of the flowfield has unburnt or burned propellants
- **Adaptive physics approach needs to be derived**
  - Apply detailed models only in specific blocks
  - Block-based solver structure is ideally suited to adaptive physics implementation

SPACE Program

Rocket Code

Software Integration
Testing
Validation
Applications

CREATE-AV Framework

Meshing
Domain Decomposition
Parallel Processing
GUI

CFD Solvers

Cartesian Solver

Strand Solver

Combustion Physics

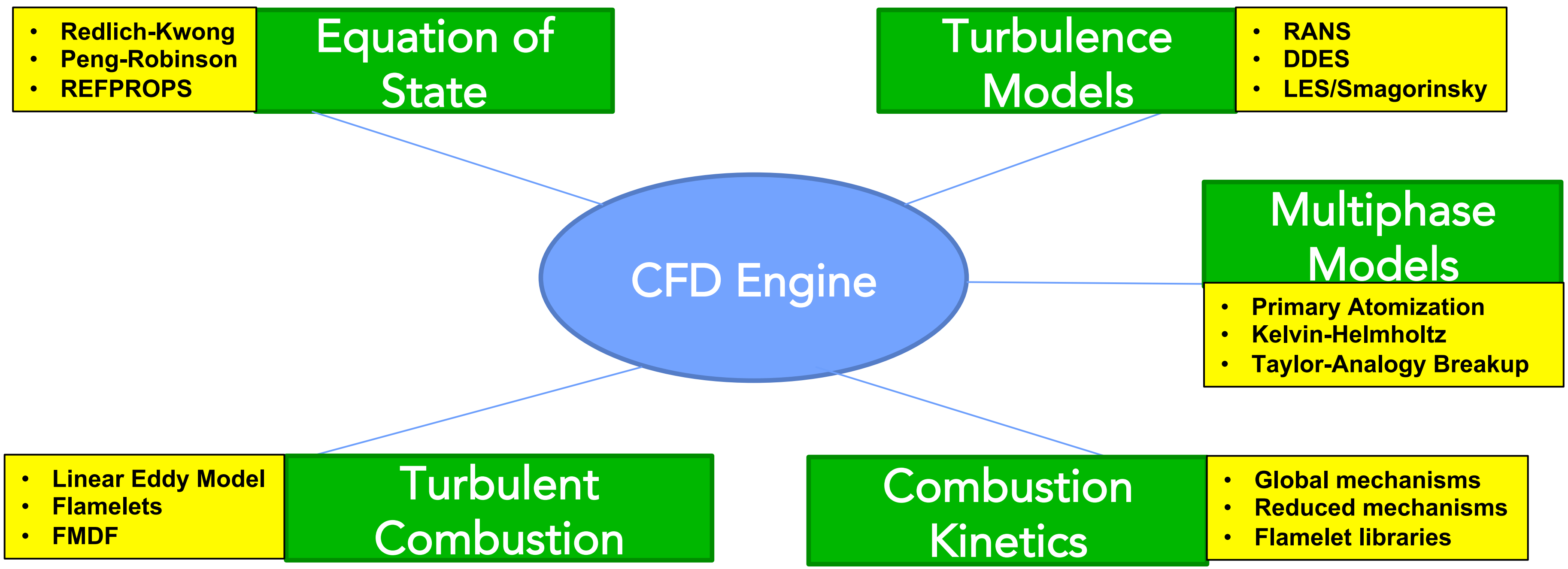
Equation of state
Turbulence
Combustion
Turbulent combustion

GPU

Multi CPU/GPU Acceleration

Version 1: Mixing & combustion
Version 2: Combustion stability
Version 3: Thermal management
Version 4: Ignition

Modular Vision



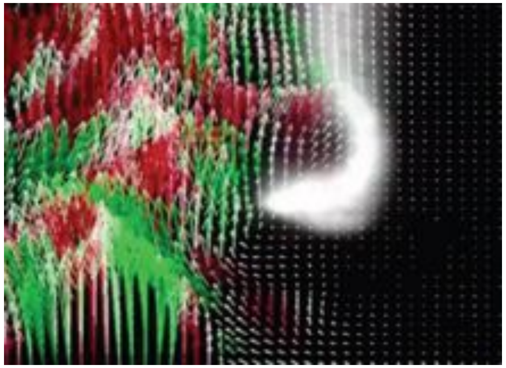
Partners:

- AFRL (East & West), HPCMO-CREATE, AEDC, Eglin
- NASA – MSFC, GRC
- DOE – Sandia/CRF, Oakridge
- Academia – Georgia Tech, Purdue, UCLA
- Industry – Aerojet-Rocketdyne, SBIR & STTR

Road Ahead

- Develop in-house code/modeling expertise
  - In-house use of codes and models developed externally
- Focus on core rocket physics expertise
  - State-of-art physics sub-models and numerics for:
    - High pressure EOS (Equation of State), LES sub-grid models, Combustion Kinetics, Multiphase, Turbulent combustion, Structures
- Modular physics with well-defined interfaces
  - Build infrastructure with core-CFD algorithms
  - Build partnerships for sub-model development
- Variable Level of Fidelity
  - Vision for model hierarchy from high fidelity physics-based models to lower-fidelity engineering models

Collaboration



- In-house Activities
  - Modeling and Simulations Forum
  - Coordination of M&S and diagnostics research
- RQ Interactions
  - CFD VTC's held periodically
  - Working groups in common interest areas – eg., turbulent combustion
- AFOSR Coordination
  - Rocket propulsion, turbulent combustion, flow control, plasmas, materials, propellants, computational math
- External
  - Collaboration with HPCMO/CREATE, NASA, Sandia, universities, industry, small businesses

Opportunities

- Multi-scale modeling of turbulent combustion
  – Compressible turbulence and reaction kinetics
- Emphasis on emerging computing architectures
  – Focus on GPUs
- Multi-fidelity hierarchy for design tool development
  – Reduced order model development
- Optimization framework for design & analysis
  – Including error estimation & uncertainty quantification
- Data analysis and processing
  – Advancing test science